7. RE-ENTRY HAZARDS

7.1 DEFINITION AND NATURE OF RE-ENTRY

Re-entry occurs when an orbiting spacecraft comes back into the Earth's atmosphere.[1] Any object placed in Earth orbit will eventually de-orbit and re-enter the atmosphere; this includes launch and breakup debris of satellites and spent rocket stages. Above 200 miles altitude, space is considered a perfect vacuum.[2] In reality, space is never a perfect vacuum and regardless of the orbital altitude of an object, it creates drag which eventually degrades the satellite's orbit. The solar wind and solar flares impinge on orbiting spacecraft and gravitational perturbations (both terrestrial and luni-solar) modify the spacecraft orbit and shorten its lifetime in space. The result is that spacecraft tend to spiral slowly towards the Earth's surface. When objects re-enter the atmosphere, their orbits decay rapidly and many of them burn up prior to impacting the Earth's surface.

There are two different sets of conditions associated with either controlled or uncontrolled de-orbit to consider when evaluating risk from re-entering satellites and other space debris.[15,16] Controlled de-orbit usually applies to manned and reusable spacecraft which are designed to survive re-entry and be recovered. In this situation, retrorockets are fired at a scheduled time in order to place the vehicle into a transfer orbit which intersects the surface of the Earth. If the Earth had no atmosphere, the intercept point would be the intended impact point. With the atmosphere, however, the vehicle decelerates further and falls short of the predicted vacuum impact point. The impact point still can be predicted reasonably accurately under these conditions. Thus, the controlled de-orbit can be planned so the spacecraft will impact near a predetermined recovery point, minimizing the risk of inadvertent impacts on ships or ground and sea structures.

There are three major sources of uncertainty associated with predicting uncontrolled re-entry characteristics, namely: the atmospheric conditions at the time an object begins to re-enter, the time of actual impact with the Earth's surface and the area in which the re-entering object will impact. These uncertainties associated with uncontrolled re-entry increase proportionately with the object's orbital altitude and on orbit lifetime.

When an object has been orbiting for a period of time, a number of changes could have taken place over its lifetime. If the spacecraft failed in some way before it reached final orbit, its orbital parameters (inclination and eccentricity) could have changed. It may have strayed from its planned orbital path, failed to achieve final orbit or broken up in an explosion causing pieces to disperse in different directions. All of these failure modes have a direct impact on the variables (surface area, mass, shape of fragments and orbital characteristics) used in the prediction of re-entry hazards.

Small changes in orbital characteristics can drastically affect the manner of an object's passage through the atmosphere. The frictional heating and drag (deceleration) experienced in the atmosphere have large effects on the object. Small deviations from the predicted conditions of re-entry may result in large differences in re-entry hazards and the associated casualty expectation (see Section 7.6). These differences could be due to further break up caused by the shock of entering the atmosphere at high velocity, the burning and ablation (vaporization) experienced during re-entry or changes in direction or velocity due to the weather and wind conditions that slow re- entering fragments differentially at lower altitudes.

7.2 ORBITAL DECAY

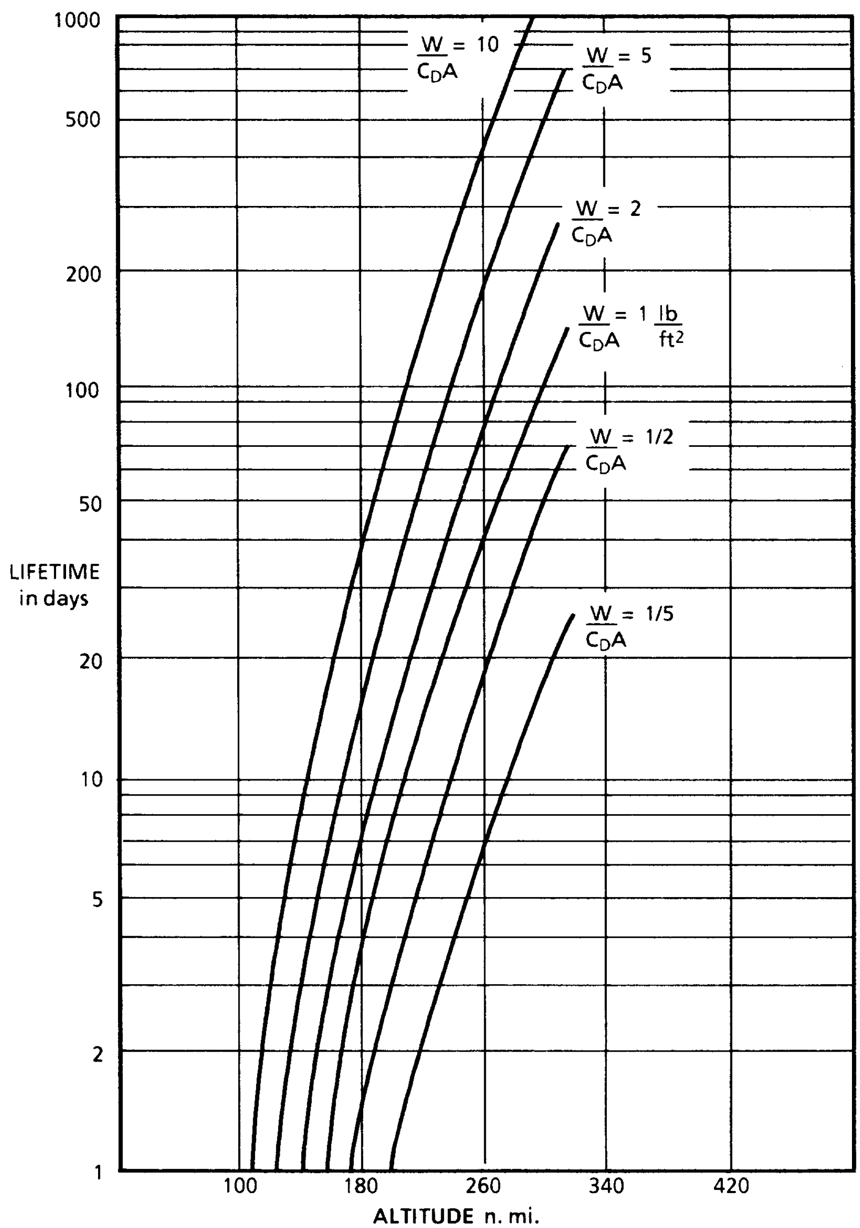
The basic concepts of energy and angular momentum (see Ch. 4) can be used to answer most questions dealing with orbital and re-entry trajectories. They are used to predict the initial re-entry point and probable ground impact points. Orbiting satellites control their positions in space by using small rocket thrusters, thereby changing their velocity and direction. This process is called "station-keeping" and requires rocket fuel and special on board communications and control equipment. Therefore, it is possible, to some extent, to choose the initial atmospheric re-entry point when dealing with controlled re-entry.[3] However, few satellites have the ability, capacity or life expectancy to provide the station-keeping capability towards the end of their life.

All space objects that orbit the Earth do so because of the various forces acting on them. These forces change the position and velocity of the object relative to Earth in such a way that their orbital characteristics become very predictable. The Satellite Surveillance Center (SSC),US Space Command (USSPACECOM), within the Cheyenne Mountain Complex in Colorado, monitors each satellite's past and present positions and predicts its future using these various orbital characteristics and dynamic processes. To determine a satellite's position at any given time, the computer uses an algorithm based on the laws of Space Mechanics.[2,3,12] The computer can predict the orbital path of the object with the object's historical position and velocity information. The Space Surveillance Center (SSC) of the US Space Command processes tracking and monitoring data obtained by the Space Surveillance Network (SSN) to predict re-entries. Space debris of the more than 90 satellite collisions or spontaneous break ups and 20 payload explosions in space have been documented to date (see also Chapter 6).[4,5,8]

External perturbations due to the Earth's oblateness, the gravitational tugs of the Sun and Moon, the solar plasma storms and atmospheric friction cause long-term changes in the orbital parameters of satellites. These forces also affect the on orbit lifetime and re-entry. Theoretically, all forces acting on near-Earth satellites can affect a satellite's on orbit lifetime. The effects of solar storms on the atmosphere and the oblateness of the Earth have a much more significant effect than the gravitational attractions of the Sun, Moon and the other planets. NASA/Marshall scientists have taken these factors into account in designing an orbital lifetime prediction program. This program, called LIFTIM, uses a direct numerical integration of the time rates of change due to atmospheric drag using a Gauss-Legendre procedure in conjunction with the Jacchia atmosphere model.[6]

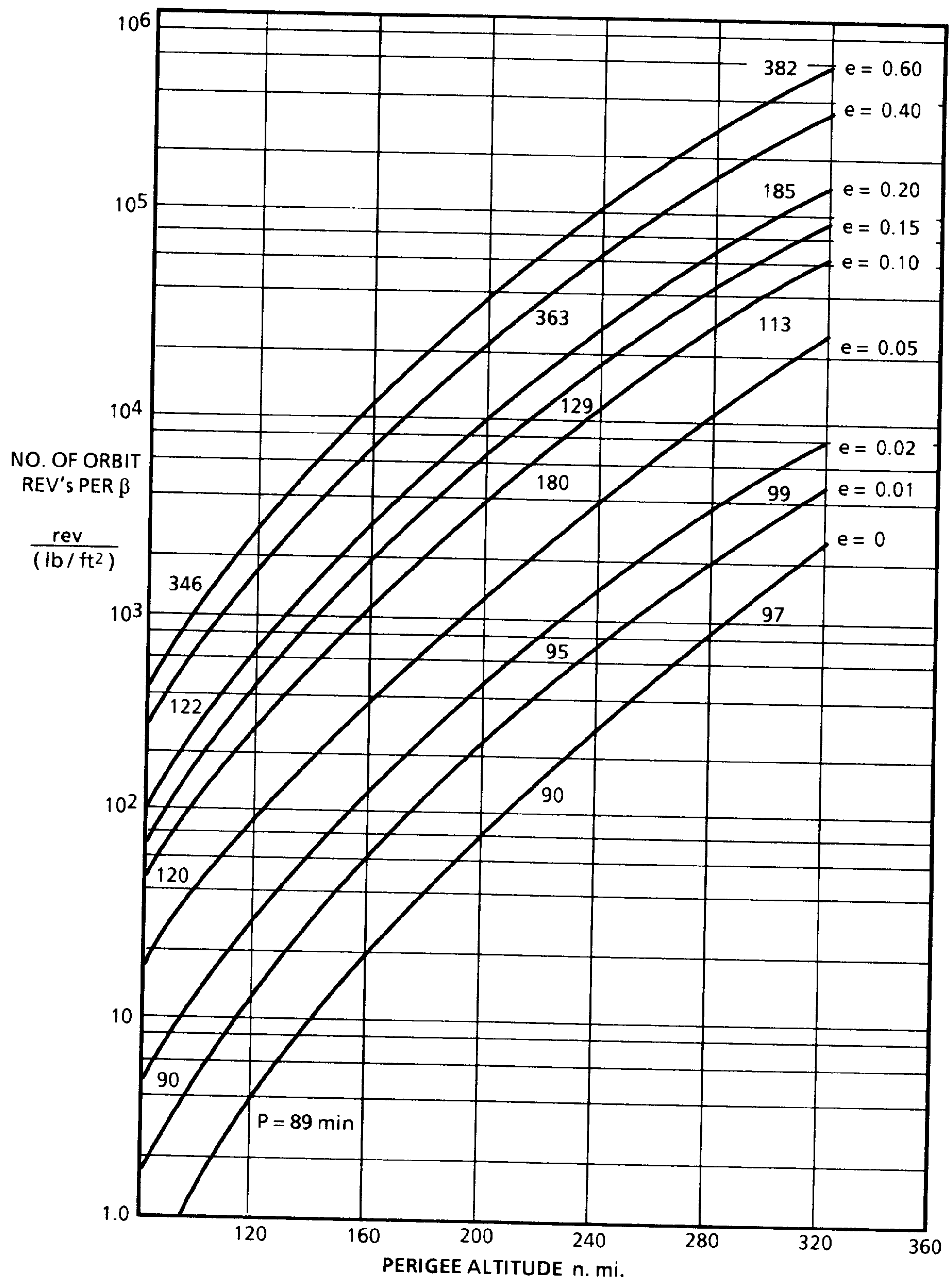
An orbiting object loses energy through friction with space plasmas above the atmosphere so that it falls into a slightly lower orbit and eventually spirals towards the Earth's surface. As the object's potential energy, represented by its altitude, is converted to kinetic energy, its orbital velocity increases. As an object's orbital trajectory is brought closer to Earth, it speeds up and outpaces others in higher orbits. Thus, a satellite's orbital altitude decreases gradually while its orbital speed increases. Once it enters the upper reaches of the atmosphere, atmospheric drag will slow it down more rapidly and eventually cause it to fall to Earth.[4]

Atmospheric drag, particularly near perigee, leads to the gradual de-orbit and re-entry of satellites. Satellites in LEO with less than 90 minute periods, corresponding to orbital altitudes of 100-200 nmi (or 185-370 km), re-enter within a couple of months. Above about 245 nmi (455 km) orbital altitudes, orbital lifetimes exceed several years. Above about 500 nmi (900 km) altitudes orbital lifetimes can be as long as 500 years.[5] Figure 7-1(a & b) illustrate Earth orbit lifetimes of satellites as a function of drag and ballistic coefficients (see Section 7-3) for circular (e=0) and elliptical orbits with a range of altitudes. For elliptical orbits, the lower the perigee altitude, the higher is the apogee decay rate (P) and the shorter the on-orbit lifetime.



NOTE 1 n. mi. = 1.852 km and 1 day = 24 hrs = 1440 min

FIGURE 7-1a. EARTH ORBIT LIFETIMES - CIRCULAR ORBITS (Ref. 1b)



NOTE: e is the eccentricity of the orbit, the ballistic coefficient, β, is assumed to be 10 lb/ft². if 1/2 β is used the decay rates are double those in the figure.

FIGURE 7-1b. EARTH ORBIT LIFETIMES - ELLIPTICAL (REF. 1b)

The ballistic coefficient á is equal to W/C_DA, where W is the spacecraft weight, C_D is the drag coefficient (which varies with shape) and A is the projected frontal area of the re-entering object. The more mass per unit area of the object, the greater the ballistic coefficient and the less the object will be consumed during its atmospheric crossing. The ballistic coefficient of a piece of debris is an important variable in the decay process as illustrated in Figure 7-1(a & b). A fragment with a large area and low mass (e.g., aluminum foil) has a low á and will decay much faster than a fragment with a small area and a high mass (e.g., a ball bearing) and will have a shorter orbital life. The combination of a variable atmosphere and unknown ballistic coefficients of spacecraft and launch and orbital debris make decay and re-entry prediction an inexact science at best.(7)

An examination of 104 successful space launches of 1985 revealed that the payloads from no less than 47 had re-entered within a year of launch. As a rule of thumb, it is suggested that about 70 percent of the annual mass put into orbit re-enters the atmosphere within 1 year of launch. Another 5 percent of the original annual mass may be expected to re-enter within 5 years from launch.(8) For example, from July 1 to October 1, 1987, of the 121 objects which de-orbited, 53 were payloads launched in that period.(17)

USSPACECOM's SSC currently tracks about 7000 cataloged objects and may issue Tracking and Impact Prediction (TIP) messages which predict re-entry times and points of impact for about 500 re-entries each year. For example, in 1979-1980, 900 new objects were cataloged, but the total tracked population decreased by 300. The satellites were "purged" during the solar sunspot maximum which effectively increased the atmospheric density in LEO, thus, increasing orbital decay rates. Atmospheric drag is directly related to solar activity: High solar activity heats the upper atmosphere, increasing the atmospheric density by more than 10 times the average density at most satellite altitudes. This exerts a greater braking force on satellites and causes an above average number of objects to re-enter the atmosphere.(9) Thus, satellites decay in much greater numbers near Sunspot maximum than at a time of low solar activity (Figure 7-2).(10) Hence, the 11 year sunspot cycle is a periodic natural "sink", removing orbiting satellites from the near-Earth environment and thereby increasing re-entry hazards.

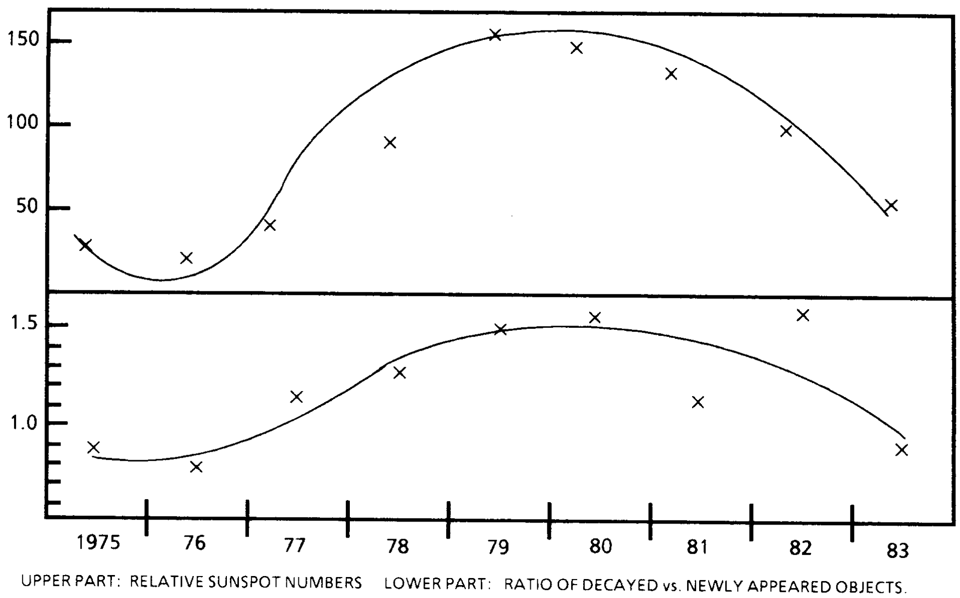


FIGURE 7-2. EFFECT OF SOLAR ACTIVITY ON SATELLITE DECAY

During the past 5 years there have been an annual average of 548 decays from lower altitude orbits (i.e., about three satellites re-entering every 2 days). Almost 83 percent of Earth satellites reside in LEO orbits (see Chapter 6) with periods of less than 225 min (about 4 hrs) and are near term re-entry candidates (see Figs.4-3 and 7-1). The total number of satellite decays per year is shown in Figure 7-3. [11]

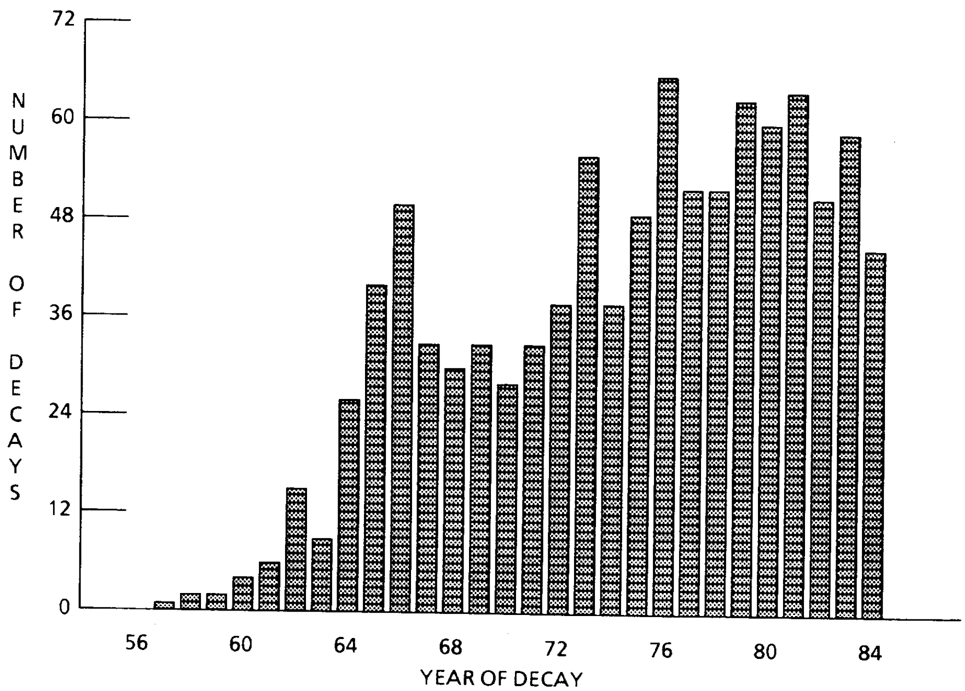


FIGURE 7-3 CATALOGED SATELLITE DECAYS

7.3 RE-ENTRY SURVIVABILITY

The information mentioned above would suffice to predict re-entry and ground impact points for spacecraft only if no other variables affected the re-entry process. In reality, the Earth's atmosphere, which is very sparse at high altitudes, interacts with the spacecraft. A vehicle approaching the Earth's atmosphere from space possesses a large amount of kinetic energy, due to its high relative velocity, and potential energy due to its orbital altitude above the Earth. When it encounters the atmosphere, a shock wave forms ahead of the vehicle, heating the atmosphere in this region to very high temperatures. The high temperatures due to friction with atmosphere reduce the vehicle's velocity and convert the vehicle's potential energy into heat absorbed by the object and its wake. If the vehicle slows down quickly, the total amount of heat to be absorbed by the vehicle is reduced. This explains the blunt (high drag) shape of re-entering spacecraft in the pre-shuttle manned space program. However, the total heat generated in the shock wave is still too great to be absorbed by metals which heat up and melt. Therefore, since it takes significantly more heat to vaporize material than to heat or melt it, materials used in heat shields were designed to ablate (vaporize) in the presence of the extreme temperatures. The net effect is that ablative protection allows objects to survive re-entry.

If the total energy of the spacecraft were converted to heat, it would vaporize the vehicle. The survival of meteorites to ground impact is proof that not all of the energy is converted into heat, but enough is converted to cause surface ablation. Actually, a large portion of the total energy is diverted away from the vehicle. If the object conducted the heat away from the forward surface and the total body could absorb the heat of re-entry without breaking up, then the object would re-enter the Earth's atmosphere and descend to Earth in a predictable way.(12) Heat shields and special shaping of forward surfaces are used to minimize frictional heating effects on the rockets and payloads during space launches, to protect them from heat and control ablation.

Surface heating effects depend on the vehicle's shape, composition, altitude and velocity. For re-entry at small angles of inclination when the vehicle deceleration rate is small, the surface heating rate is correspondingly small. For re-entry at large angles of inclination where the vehicle decelerates rapidly in the atmosphere, the surface heating rate will be greater but the time spent in the atmosphere will be shorter.(3)

Spacecraft which are not designed to survive re-entry generally do not have ablative surfaces nor are they very stable aerodynamically. The usual sequence of events in the re-entry process is as follows:

1. As the vehicle starts to re-enter, heat is generated by the shock wave and a portion is absorbed by the surface of the structure. As the structure heats up thermal energy is radiated out at a significantly lower rate than it is being absorbed.

2. The heated structure weakens and when the aerodynamic forces exceed its structural strength, it starts to come apart.

3. The heating process continues on the remaining parts of the structure, repeatedly breaking it up into still smaller pieces.

4. These structural pieces continue to heat up and eventually melt and vaporize if there is sufficient temperature and time exposure. Some structural elements can survive if they are massive or were shielded from the heat by other parts of the structure.

After the atmospheric re-entry point has been predicted, various other conditions must be taken into account to predict a ground impact point. Some of these conditions are orbital corrections due to frictional heating, break up due to atmospheric shock, drag and prevailing meteorological conditions. All of these factors are important when assessing the hazards from re-entering objects to people and property.[12]

7.4 RE-ENTRY IMPACT PREDICTION

The ground trace of an orbit is the path over which the satellite orbits the Earth (see Figure 7-4). If there were a string between the center of the Earth and a satellite, the course marked by the intersection of the string with the surface of the Earth would be the trace of the orbit. Depending on the orbit, this ground trace could cover a large portion of the surface of the Earth (see Figure 7-5). If a satellite is tracked on a regular basis, it is possible to anticipate its approximate re-entry time and make an approximate prediction of the impact point. However, this does not give control over the position of the impact point and impact prediction uncertainties are usually rather large (on the order of 10's to 100's of miles).

One of the most critical factors in the re-entry process is the ballistic coefficient of the object, as discussed above. The ballistic coefficient is the ratio of gross weight to the drag coefficient multiplied by the reference area (W/C_DA). The relationship between the ballistic coefficient and the orbital lifetime is also linear, as illustrated in Figure 7-1(a & b). Small particles tend to have shorter lifetimes at a given orbital altitude than larger ones. This has been observed in the case of solid rocket motor debris where measurements made shortly after motor firings have shown a rapid increase in debris levels, but relatively rapid decay of small debris.

A second indirect confirming observation is the shape of the debris flux curve as a function of debris size.[13]
(See Chapter 6).

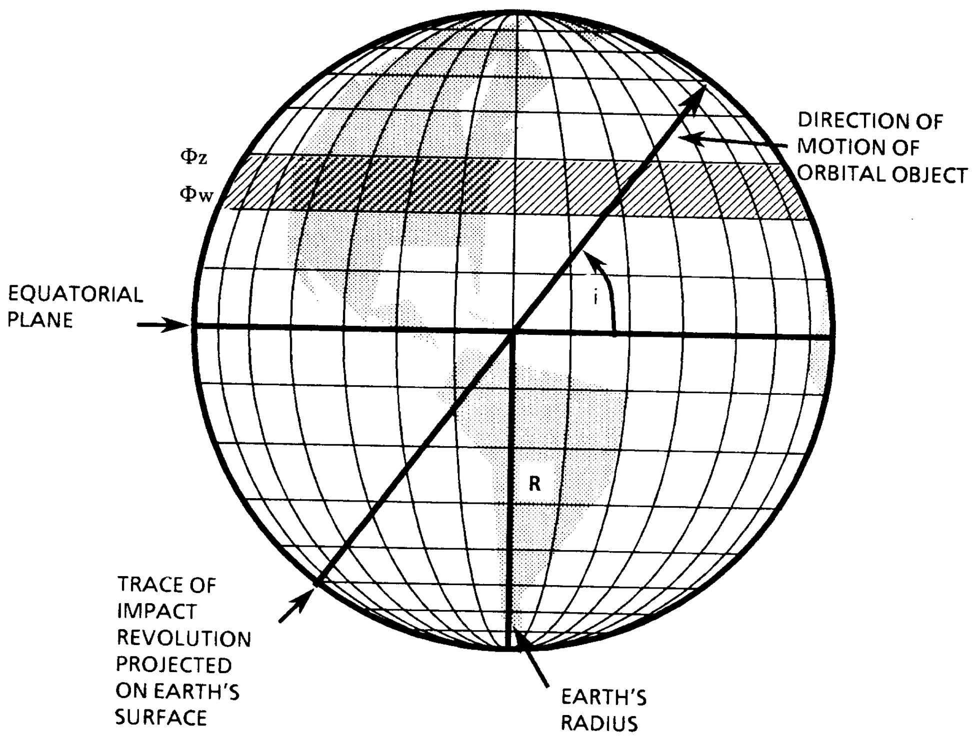


FIGURE 7-4 PLAN VIEW OF THE EARTH AND GROUND TRACK

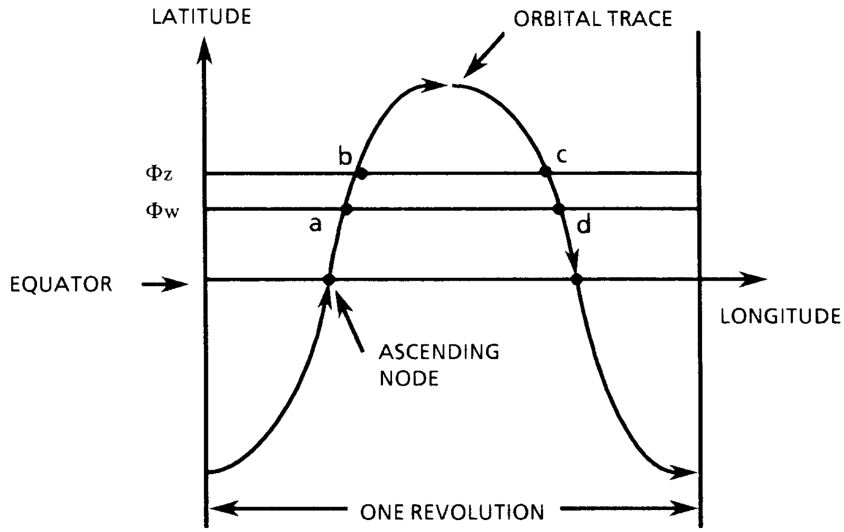


FIGURE 7-5 ORBITAL TRACE GEOMETRY

As a satellite re-enters the atmosphere it decelerates. As discussed above, the deceleration rate is a function of many variables: entry angle, lift to drag ratio (L/D), the ballistic coefficient, the orbital parameters, the Earth's rotation and oblateness, atmospheric density aberrations and winds. The entry angle and ballistic coefficient affect the chance that a satellite or debris object will survive re-entry and landing. The satellite may skip due to the lift caused by the object's angle of attack upon entering the atmosphere, each skip associated with a change in velocity, speed and entry angle. As discussed in Chapter 4, every orbit has an angle of inclination, which along with the apogee and perigee, defines the trace of an orbit.

During re-entry the original orbital inclination of the satellite remains relatively constant. This holds for the inclination angle of pieces of the satellite that return separately as well as pieces of a satellite which break up during re-entry. This near consistency holds because the magnitude of the orbital velocity in the inclination plane is very large. A vertical (radial) change in velocity does not change the orbital angle of inclination, but it changes the atmospheric entry angle (called radiant). A change in the velocity component perpendicular to the plane of the orbit may affect the angle of inclination, but the magnitude of this change is minor compared to the magnitude of the velocity in the orbital plane.

7.5 IMPACT DISPERSIONS

Most satellites to date have been inserted into orbit with little or no consideration given to their eventual re-entry. The primary reason for this is that re-entering satellites are not likely to result in hazardous impacts given that 2/3 of the Earth's surface area is covered by oceans. Most of the objects which re-enter are likely to fragment and burn up in the upper atmosphere and make only negligible changes in its chemical composition. Even if an object does survive, only one third of the Earth is land area and only a small portion of this land area is densely populated, so the chance of hitting a populated land area upon re-entry is relatively small.

There is no standard way of computing impact dispersions currently. The calculations are two-fold. Estimates must be made for the number of pieces which will survive re-entry and the area over which each piece could cause damage, the "casualty area." For each piece of debris that will survive re- entry, a man-border area is added to the representative area of each incoming piece (see Volume 3, Chapter 10). The representative area is the maximum cross section area of the re-entering piece of debris. The man-border allowance is usually a ten inch addition in the radius to allow for the center of a person standing outside the actual impact radius but close enough to be hurt.[16] The splatter and rebound of fragments from hard ground impact must also be considered in these calculations.

7.6 RE-ENTRY HAZARD ANALYSIS

Most re-entering satellites and space debris are not controlled and the uncertainties of orbital decay are such that impact areas cannot be determined. Re-entry risk estimation generally assumes that the satellite can impact anywhere on Earth between the maximum northern and southern latitudes associated with the inclination of the orbit (see Figure 7-4).[16] Uncontrolled re-entry may be due to launch failures when the spacecraft fails to achieve final orbit, when the perigee/apogee kick motors malfunction and retain the satellite in a degradable transfer orbit or from second and upper stages jettisoned in orbit after burn out.

The probability of a re-entering spacecraft and/or its fragments landing within a particular latitude band depends on both the orbital inclination and the latitude spread of the ground track. Satellites in orbit spend disproportionately more time within the 1^o wide band near the maximum latitudes. This is due to the change in direction of the satellite in this area, illustrated in the orbital ground trace of Figure 7-5, and is clearly visible in the probability distributions shown in Figure 7-6. In this figure the sharp peaks for each angle of inclination occur in a very small range around the latitude extremes. The probability of impacting within a specified longitude range is assumed to be uniform (equi-probability over 360^o of longitude). A corresponding bivariate probability density can be constructed for the location of such random debris impact. This assumes that the satellite or debris from the satellite survive the aerodynamic heating of re-entry. Once the probability density for ground impact has been established, the distribution of population within the probable impact area must be considered, as shown in Figure 7-7.[15] In this figure the population distribution is combined for the northern and southern hemispheres as a matter of convenience. Although the population number and distribution has changed in the interim, the approach used in Fig. 7-7 is still valid.[15] An orbiting object will spend an equal amount of time, within a certain band width, on both the north and south sides of the equator.

The casualty expectation is usually computed using the formula:

$$E_c = P_i \times \text{(Population Density)} \times A_c$$

Where P_i is the impact probability, the population density is the number of inhabitants per unit area, and A_c is the casualty area of the debris that survive to impact. Figure 7-8 presents an updated world-wide (average) casualty expectation, as a function of orbital inclination angle and debris impact casualty area.[19] In the example shown, a satellite in an orbit inclined at 26^O, with debris having a casualty area of 100 sq. ft., will produce "on the average" 1.2×10^{-4} casualties upon re-entry.[15,19] This translates to one chance in 8333 of a casualty resulting from re-entry of this satellite. This is due to the unpredictability of the impact area during uncontrolled re-entry as opposed to the localized casualty area during launch.

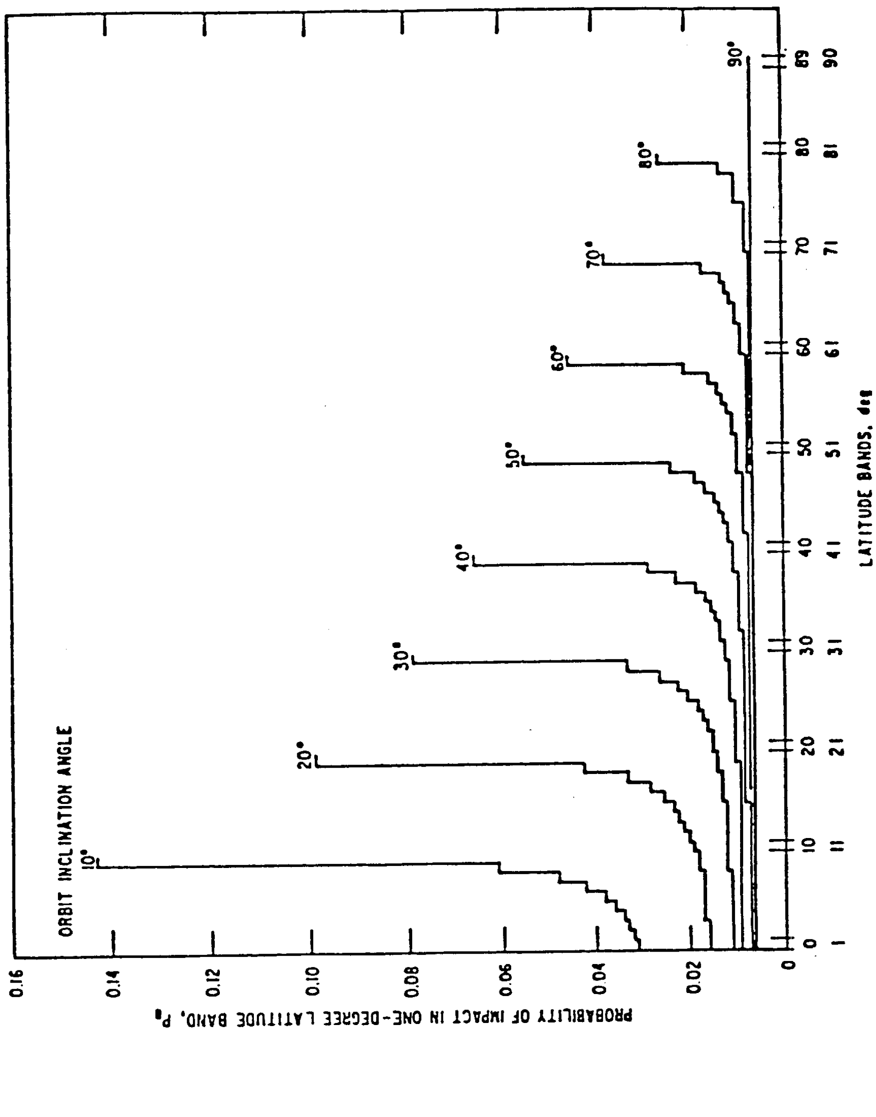


FIGURE 7-6 PROBABILITY OF IMPACT IN ONE-DEGREE LATITUDE BANDS (REF. 15)

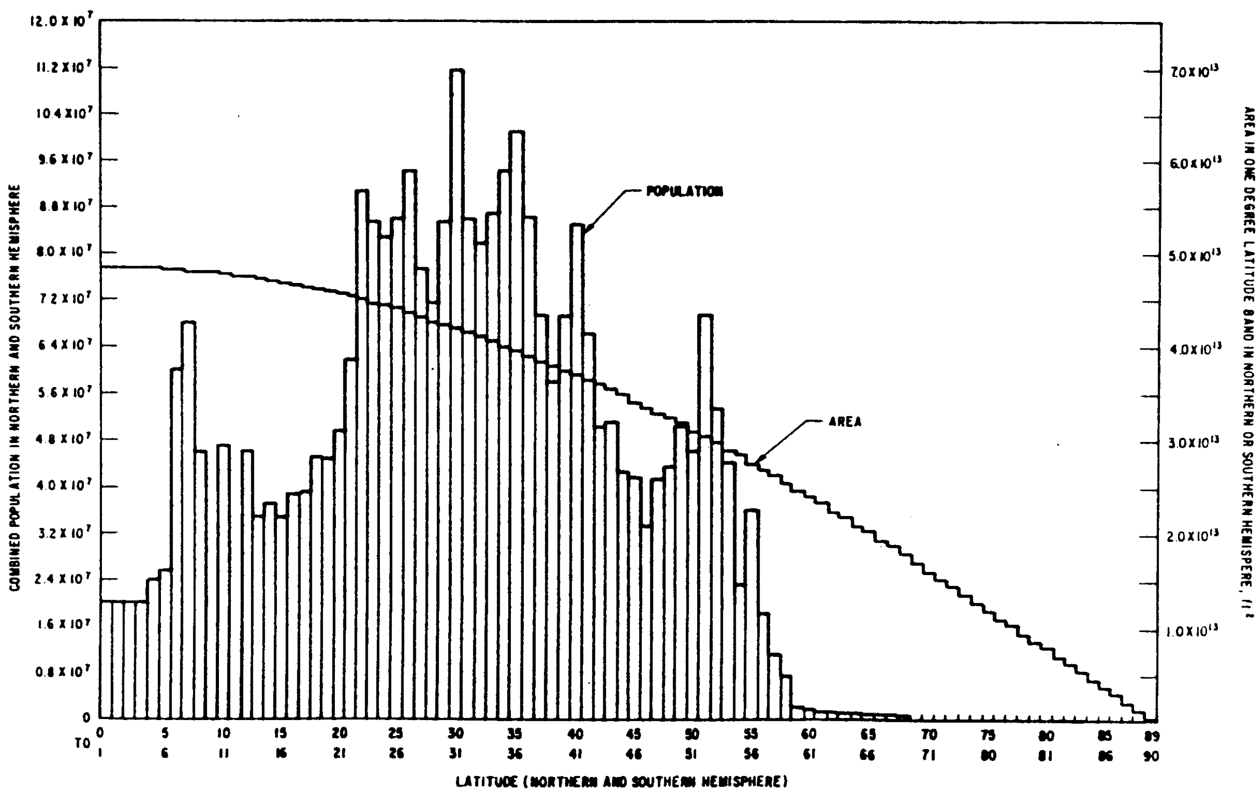


FIGURE 7-7 POPULATION AND AREA DISTRIBUTION OF THE WORLD BY ONE-DEGREE LATITUDE BANDS (POPULATION STATISTICS FOR 1965)

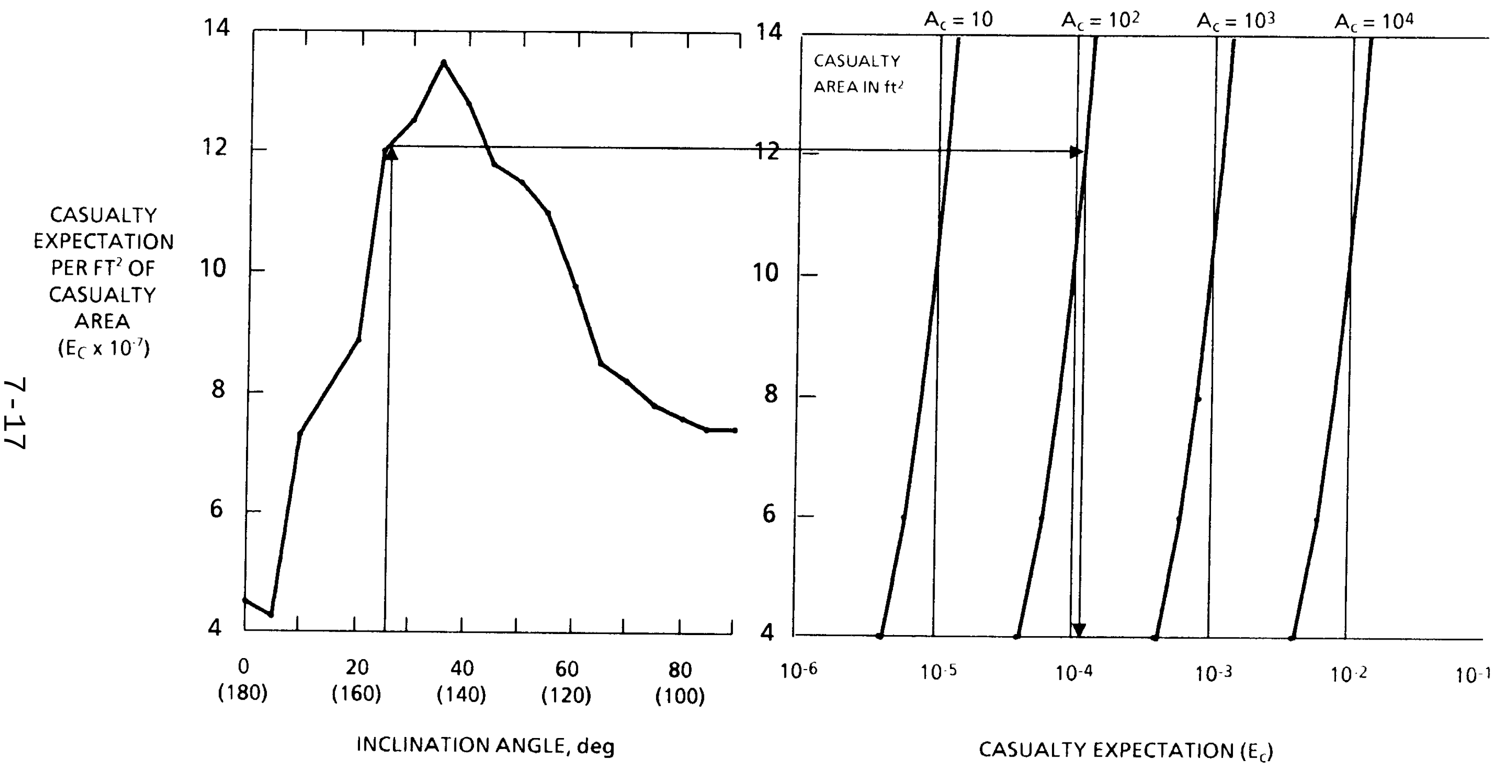


FIGURE 7.8 WORLD-WIDE CASUALTY EXPECTATION vs. ORBIT INCLINATION ANGLE (POPULATION ESTIMATED FOR 1990) (REFS. 15, 19)

With no control over the time and location of re-entry, impact could occur in any country between the latitudes of ± 26^0.[16,18] Up to now, there have been no reported land impacts, damage and/or casualties by re-entry debris.[20] Roughly 100 of the approximately 3,100 objects resulting from 44 launches between 1956-1972 have survived re-entry and were recovered.[20] Identified re-entry debris include such diverse items as: tank pieces, nozzle pieces, small spherical gas tanks, plastic shrouds and other fragments.[20]

Particular re-entry hazards to the public are posed by orbiting nuclear payloads. Since 1961, both the US and the Soviet Union have launched nuclear power cells into space (See Table 7-1). While there have been no commercial payloads with nuclear materials, it is important to discuss generic re-entry hazards of this type. To date , such missions have required detailed risk analysis and interagency review. However, the US has launched passive, naturally decaying nuclear fuel cells, while the USSR has orbited RORSAT satellites with active nuclear reactors at relatively low altitudes in orbits which decay in a matter of days to weeks. Twenty eight such Soviet nuclear satellites were launched between 1967 and 1985, each carrying roughly 50 kg of U^{235}. Of these, 26 have been transferred successfully into higher altitude parking orbits (over 900 km) at their end of duty to permit decay of radionuclides before re-entry. However, at least six have failed and undergone uncontrolled re-entry and atmospheric break up, one showering debris over N. Canada in 1978 and two others over the Indian Ocean in 1983 and 1987. In contrast, the US nuclear fuel cells are designed to survive atmospheric re-entry and impacts. Three radio-isotope thermal generator (RTG) power supplies accidentally re-entered as a result of launch and/or orbital insertion failures (in 1964,1968 and 1970); no undue public exposure to radioactivity resulted from any of these.[14]

Although the possibility of a satellite landing in a populated area is small, the hazards are real and in certain instances, potentially very serious. Cosmos 954, the Soviet nuclear satellite that scattered nuclear debris over Canada upon re-entry and caused over $12 million in damages and cleanup costs is one example of a potentially serious re-entry hazard.[21] Fortunately, several other failed or deactivated Soviet RORSAT and US nuclear satellites have returned over oceans (Table 7-1). Issues related to re-entry hazards are currently under active re-examination and are undergoing research.

TABLE 7-1 RE-ENTRIES OF SPACE NUCLEAR POWER SUPPLIES (REF. 15)

	NAME	LAUNCH DATE	RE-ENTRY	TYPE OF POWER SUPPLY	COMMENTS
USA	Transit 5 BN3	21 April 1964	21 April 1964	Radioisotope	Launch failure. SNAP 9A destroyed over Indian Ocean
	Nimbus B	18 May 1968	19 May 1968	Radioisotope	Launch failure. SNAP 19 recovered off California coast.
	Apollo 13	11 April 1970	17 April 1970	Radioisotope	SNAP 27, designed for deposit on lunar surface, re-entered over Pacific Ocean during emergency return of Apollo 13 astronauts.
USSR	-	25 January 1969	25 January 1969	Reactor	Possible launch failure of ocean surveillance satellite.
	Kosmos 300	23 September 1969	27 September 1969	Radioisotope	One or both of these payloads may have been a Lunikhod, designed for remote exploration of the Moon carrying a Po^{210} heat source. Upper stage malfunction prevented payloads from leaving Earth orbit.
	Kosmos 305	22 October 1969	24 October 1969		
	-	25 April 1973	25 April 1973	Reactor	Possible launch failure of ocean surveillance satellite.
	Kosmos 954	18 September 1977	24 January 1978	Reactor	Payload malfunction caused re-entry near Great Slave Lake in Canada. Local contamination detected.
	Kosmos 1402	30 August 1982	23 January 1983	Reactor	Payload Failed to boost to storage orbit on 28 December 1982.
			7 February 1983	Fuel core	Reactor re-entered at 25° S, 84° E. Fuel core re-entered at 19° S, 22° W.

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